

Restless Quasar Activity: From *BeppoSAX* to *Chandra* and XMM-*Newton*

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We briefly review some of the progress made in the last decade in the study of the X-ray properties of the quasar population from the luminous, local objects observed by *BeppoSAX* to the large, rapidly increasing population of $z > 4$ quasars detected by *Chandra* and XMM-*Newton* in recent years.

1. Introduction

Over the last decade *ASCA* and *BeppoSAX* have significantly improved our knowledge of the X-ray properties of Active Galactic Nuclei (AGNs), especially at low redshifts, thanks to their broad-band coverage and relatively large effective areas above 2 keV. Moreover, the unique X-ray coverage above ≈ 10 keV (up to ≈ 100 –200 keV) provided by the Phoebus Detector System (PDS) onboard *BeppoSAX* has allowed proper definition of intrinsic X-ray continuum shapes of local Seyfert galaxies (e.g., [1,2,3,4]; see also [5], this Volume) and quasars (e.g., [6]).

In Section 2 we will briefly recall the most important *BeppoSAX* results obtained for a peculiar AGN: the luminous, nearby radio-quiet quasar (RQQ) PDS 456.

Although a few X-ray spectral studies of quasars at $z \approx 2$ –3 have been carried out with *ASCA* (e.g., [7,8]) and *BeppoSAX* (e.g., [9]), the properties of luminous RQQs at higher redshifts ($z > 4$) were poorly known before the launches of the current generation of X-ray telescopes, *Chandra* and XMM-*Newton*. In Section 3 we will discuss the large improvements that have occurred in this field in the last few years.

2. One “intriguing” *BeppoSAX* observation: Warm and cold absorption in the luminous, nearby RQQ PDS 456

Unfortunately, high-luminosity quasars are usually found at relatively high redshifts, thus appearing rather weak and difficult to study in X-rays before the launches of *Chandra* and XMM-*Newton*. In this context, PDS 456, at $z = 0.184$ and with $L_{\text{bol}} \simeq 10^{47}$ erg s⁻¹, can be considered an exceptional case, thus allowing an accurate modeling of the X-ray continuum and reprocessing features with both *BeppoSAX* and *ASCA* ([10]) and, recently, with XMM-*Newton* ([11]). The X-ray spectrum of PDS 456 is characterized by a prominent ionized Fe K edge [clearly visible in the data-to-model residuals shown in Fig. 1, panel (a), when a single power-law fit is adopted]; the edge corresponds to Fe XXIV-XXVI at ≈ 8.8 keV [see Fig. 1, panel (b)]. The lack of iron emission lines suggests that the ionized edge is due to matter along the line-of-sight rather than reflection from a highly ionized accretion disk. Indeed, the hard X-ray continuum is due to transmission through a very ionized medium, best fitted by a column density $N_{\text{Hwarm}} \approx 4.5 \times 10^{24}$ cm⁻², coupled with absorption by cold matter having $N_{\text{Hcold}} \approx 2.7 \times 10^{22}$ cm⁻² ([10]; see Fig. 2 for the best-fit spectrum).

The X-ray properties of PDS 456 appear quite different from those of the majority of the local

*Support from the Italian Space Agency under contract ASI I/R/073/01 is acknowledged.

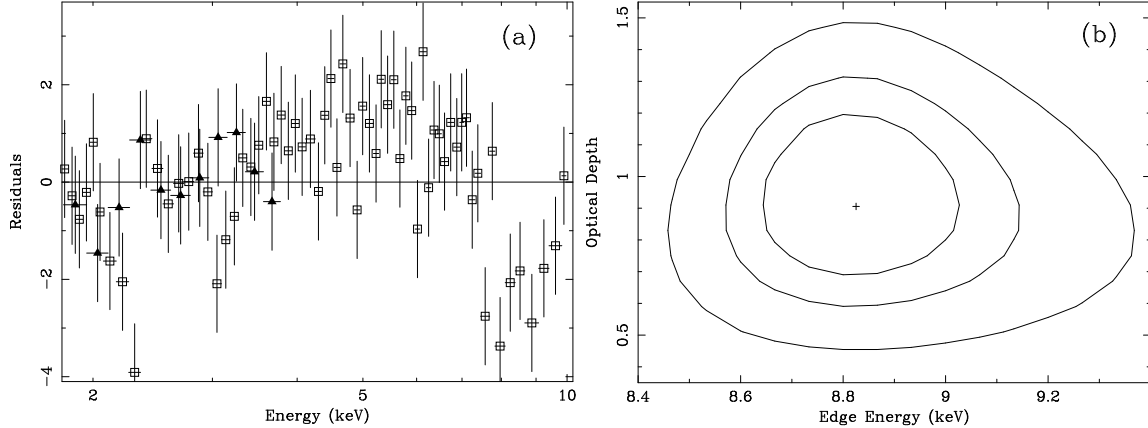


Figure 1. (a) Data-to-model residuals for a single power-law fit to the LECS (triangles) and MECS (squares) data of PDS 456. (b) 68, 90, and 99% confidence regions for the rest-frame edge energy versus the optical depth derived from the *BeppoSAX* spectrum of PDS 456 assuming model (B) in [10].

Palomar-Green quasars (e.g., [6,12]); its photon index is rather flat ($\Gamma = 1.4 - 1.6$; see [10]) and the absorber ionization parameter $U = \frac{n_{\text{phot}}}{n_e}$, defined as the ratio of the ionizing photon density at the surface of the cloud to the electron density of the gas, is extremely high (≈ 7900 ; see [10]). This overall X-ray picture for PDS 456 has been confirmed recently by *XMM-Newton*, whose spectral resolution has allowed three high-ionization iron K edges ([11]) to be distinguished instead of the one observed by *BeppoSAX* (likely due to the different spectral resolution and effective area). *XMM-Newton* has also discovered an extreme gas outflow velocity of $\approx 50,000 \text{ km s}^{-1}$ ([11]), thus supporting the idea that the ionized matter is close to the active nucleus of PDS 456. Furthermore, the source showed repeated X-ray flaring episodes, with an X-ray flux doubling time of $\approx 30 \text{ ks}$ and a total energy output of the flaring events as high as 10^{51} erg [13]. This extreme X-ray variability and the presumably high accretion rate make this source more similar to the Narrow-Line Seyfert 1 galaxies. High-resolution X-ray spectroscopy of such objects can provide further details on the accretion mechanisms responsible for the X-ray emission in high-luminosity objects (e.g., [11,14]).

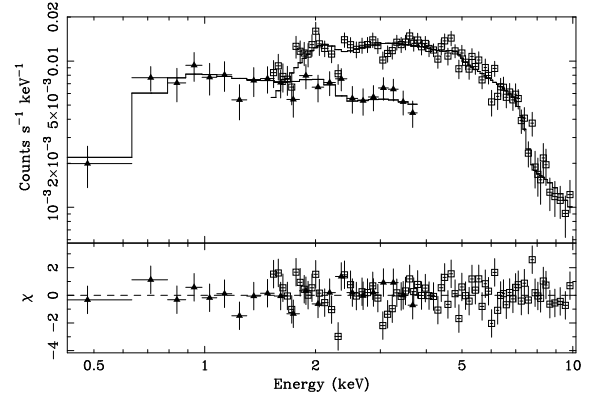


Figure 2. *BeppoSAX* LECS (triangles) and MECS (squares) 0.5–10 keV spectrum of PDS 456. The data-to-model residuals are shown in the bottom panel in units of σ .

3. The realm of the ancient quasars

The last few years evidenced an increasing interest in the study of $z \gtrsim 4$ AGNs (mainly quasars), including in the X-ray band. Prior to 2000 there were only six quasars at $z > 4$ with X-ray detections. The number of X-ray detected quasars at $z > 4$ doubled when the first systematic X-ray study of these objects was carried out using archival *ROSAT* data ([15]). Since then,

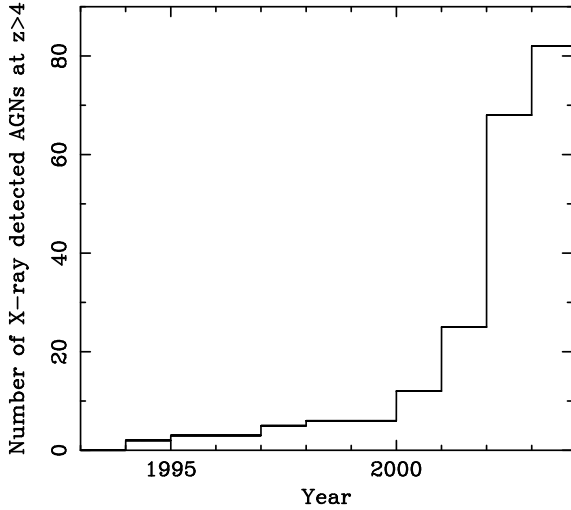


Figure 3. Cumulative number of $z > 4$ X-ray detected AGNs as a function of year.

the progress made in this field has been substantial. This has been possible due to the availability of increasing numbers of $z > 4$ quasars from ground-based optical surveys (e.g., the Sloan Digital Sky Survey – SDSS, [16], the Digital Palomar Sky Survey – PSS, [17], and the Automatic Plate Measuring facility survey – APM, [18]),² and the excellent capabilities of *Chandra* and *XMM-Newton* for detecting faint sources.

To define the basic individual X-ray properties (i.e., X-ray fluxes, luminosities, and optical-to-X-ray spectral indices) of $z > 4$ quasars, we started a program to observe with *Chandra* and *XMM-Newton* both the optically brightest $z \approx 4$ –4.6 PSS/APM quasars and the higher redshift, optically fainter SDSS quasars ([19,20,21, 22,23]; see also the recent review by [24]). Since the pioneering work with *ROSAT* ([15]), the number of AGNs with X-ray detections has therefore increased significantly to more than 80 (see Fig. 3),³ in the redshift range $z \approx 4$ –6.3 (also see [25,26,27,28,29]). Due to the extremely low

²See <http://www.astro.caltech.edu/~george/z4.qsos> for a listing of high-redshift quasars.

³See <http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat> for a regularly updated listing of X-ray detections and sensitive upper limits at $z > 4$.

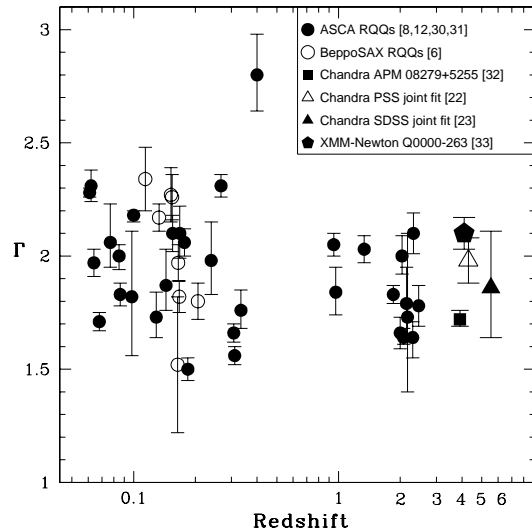


Figure 4. Plot of photon index versus redshift for optically selected RQQs. Different symbols indicate different samples (as shown in the key; also see [23] for details). No clear indication of X-ray continuum evolution with redshift is seen.

background in typical *Chandra* snapshot (≈ 4 –10 ks) observations, it has also been possible to derive average spectral constraints for subsamples of high-redshift quasars using joint spectral fitting with ≈ 120 –340 X-ray counts ([22,23]). At $z > 4$, optically selected RQQs have a photon index of $\Gamma \approx 1.8$ –2.0, similar to the results found at low and intermediate redshifts (e.g., [12]). Furthermore, no spectral evolution of the X-ray continuum shape over cosmic time has been found (see [23] and Fig. 4). At high redshift, this result has been supported recently by direct X-ray spectroscopy of QSO 0000–263 at $z = 4.10$ with *XMM-Newton* ([33]).

REFERENCES

1. G. Matt, in X-ray Astronomy: Stellar End-points, AGN, and the Diffuse X-ray Background, N.E. White, G. Malaguti, G.G.C. Palumbo (eds.), AIP Conf. Proc. 599 209 (2001).

2. G. Risaliti, *A&A* 386 379 (2002).
3. S. Deluit and T.J.-L. Courvoisier, *A&A* 399 77 (2003).
4. A. Malizia, L. Bassani, J.B. Stephen, G. Di Cocco, F. Fiore and A.J. Dean, *ApJ* 589 L17 (2003).
5. P.O. Petrucci and M. Dadina, this Volume (2003).
6. T. Mineo et al., *A&A* 359 471 (2000).
7. M. Cappi, M. Matsuoka, A. Comastri, W. Brinkmann, M. Elvis, G.G.C. Palumbo and C. Vignali, *ApJ* 478 492 (1997).
8. C. Vignali, A. Comastri, M. Cappi, G.G.C. Palumbo, M. Matsuoka and H. Kubo, *ApJ* 516 582 (1999).
9. M. Elvis, F. Fiore, A. Siemiginowska, J. Bechtold, S. Mathur and J. McDowell, *ApJ* 543 545 (2000).
10. C. Vignali, A. Comastri, F. Nicastro, G. Matt, F. Fiore and G.G.C. Palumbo, *A&A* 361 69 (2000).
11. J.N. Reeves, G. Wynn, P.T. O'Brien and K.A. Pounds, *ApJ* 593 L65 (2003).
12. I.M. George, T.J. Turner, T. Yaqoob, H. Netzer, A. Laor, R.F. Mushotzky, K. Nandra and T. Takahashi, *ApJ* 531 52 (2000).
13. J.N. Reeves, G. Wynn, P.T. O'Brien and K.A. Pounds, *MNRAS* 336 L56 (2002).
14. K.A. Pounds, J.N. Reeves, A.R. King, K.L. Page, P.T. O'Brien and M.J.L. Turner, *MNRAS*, in press, astro-ph/0303603 (2003).
15. S. Kaspi, W.N. Brandt and D.P. Schneider, *AJ*, 119 2031 (2000).
16. D.G. York et al., *AJ* 120 1579 (2000).
17. S.G. Djorgovski, R.R. Gal, S.C. Odewahn, R.R. de Carvalho, R. Brunner, G. Longo and R. Scaramella, in *Wide Field Surveys in Cosmology*, S. Colombi and Y. Mellier (eds.), Editions Frontieres, 89 (1998).
18. M. Irwin, R.G. McMahon and C. Hazard, in *The space distribution of quasars*, D. Cramp-ton (ed.), ASP Conf. Ser. 21 117 (1991).
19. W.N. Brandt, M. Guainazzi, S. Kaspi, X. Fan, D.P. Schneider, M.A. Strauss, J. Clavel and J.E. Gunn, *AJ* 121 591 (2001).
20. C. Vignali, W.N. Brandt, X. Fan, J.E. Gunn, S. Kaspi, D.P. Schneider and M.A. Strauss, *AJ* 122 2143 (2001).
21. W.N. Brandt et al., *ApJ* 569 L5 (2002).
22. C. Vignali, W.N. Brandt, D.P. Schneider, G.P. Garmire and S. Kaspi, *AJ* 125 418 (2003).
23. C. Vignali, W.N. Brandt, D.P. Schneider, S.F. Anderson, X. Fan, J.E. Gunn, S. Kaspi, G.T. Richards and M.A. Strauss, *AJ* 125 2876 (2003).
24. W.N. Brandt et al., in *New X-ray Results from Clusters of Galaxies and Black Holes*, C. Done, E.M. Puchnarewicz and M.J. Ward (eds.), *Adv. Sp. Res.*, in press, astro-ph/0212082 (2003).
25. D.P. Schneider, M. Schmidt, G. Hasinger, I. Lehmann, J.E. Gunn, R. Giacconi, J. Trümper and G. Zamorani, *AJ* 115 1230 (1998).
26. C. Vignali, F.E. Bauer, D.M. Alexander, W.N. Brandt, A.E. Hornschemeier, D.P. Schneider and G.P. Garmire, *ApJ* 580 L105 (2002).
27. J.D. Silverman et al., *ApJ* 569 L1 (2002).
28. J. Bechtold et al., *ApJ* 588 119 (2003).
29. F.J. Castander, E. Treister, T.J. Maccarone, P.S. Coppi, J. Maza, S.E. Zepf and R. Guzman, *AJ* 125 1689 (2003).
30. C. Vignali, A. Comastri, M. Cappi, G.G.C. Palumbo and M. Matsuoka, in *X-ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-ray Background*, N.E. White, G. Malaguti, G.G.C. Palumbo (eds.), AIP Conf. Proc. 599 999 (2001).
31. J.N. Reeves and M.J.L. Turner, *MNRAS* 316 234 (2000).
32. G. Chartas, W.N. Brandt, S.C. Gallagher and G.P. Garmire, *ApJ* 579 169 (2002).
33. E. Ferrero and W. Brinkmann, *A&A* 402 465 (2003).